Design and Performance Evaluation of an Indirect Evaporative Air Cooler

V. Sudheer Kumar Reddy[1], Praveen.S[2], and Jaywant H. Arakeri[2]
[1]Indian Institute of Science/ Mechanical Engineering, Bangalore, India
Email: sudheerv10@gmail.com
[2]Indian Institute of Science/ Mechanical Engineering, Bangalore, India
Email: jaywant@mecheng.iisc.ernet.in

Abstract: This paper presents design of small indirect evaporative air cooler which is developed as a cross flow heat exchanger and its performance evaluation under controlled environmental conditions. The experimental results are compared with the results of an analytical model developed by assuming constant water film temperature on the heat exchanger tubes. The experimental results of the cooler show a satisfactory agreement with the analytical values. The analytical results show that low inlet humidity and higher inlet temperature of the comfort air results in an increase in both cooling effect and cooling capacity. A very low velocity of comfort air gives more cooling effect but the cooling capacity declines. For given inlet conditions and for given length of the tubes, a tube diameter of around 2 mm results in better cooling capacity.

Index Terms: **Evaporative cooling; Cross flow; Heat exchanger; Cooling effect; Cooling capacity**

I. Introduction

Evaporative cooling is an alternative and efficient method of cooling in dry climates. Evaporative cooling occurs when moisture is added to air, which is not saturated (i.e., relative humidity is less than 100%). When the evaporation of a liquid into surrounding air takes place, it cools the objects or a liquid in contact with it. The relative humidity of the air is decided by the dry and wet bulb temperatures. The wet bulb depression (temperature difference between dry bulb and wet bulb temperatures) is the measure of potential for evaporative cooling. Greater the wet bulb depression greater is the cooling effect, and vice versa. When the dry bulb and wet bulb temperatures are same, i.e., 100% relative humidity, no net evaporation of water in to the air occurs, thus there is no cooling effect. Evaporative cooling is a very common form of cooling buildings for thermal comfort since it is relatively cheap and requires less energy than conventional air conditioning systems. Modern technology has dramatically increased the efficiency and effectiveness of evaporative cooling systems.

Direct evaporative coolers uses latent heat of evaporation to lower the temperature of air. In this process, the air stream to be cooled is in direct contact with water and cooling is accomplished by the adiabatic heat exchange between air and water. Direct evaporative cooling systems are suitable for use only in dry and arid climates where both cooling and humidification is needed. Allergies caused by the wet cooling pads is the another drawback of direct evaporative cooling. The thermal analysis of an indirect evaporative cooling is complicated as it involves simultaneous heat and mass transfer at air and water film interface. Pascal Stabat and Marchio[1] describes a simplified model for indirect-contact evaporative cooling tower behaviour by using the Effectiveness-NTU method. In this model the water film temperature is assumed to be constant along the coil. This theoretical model is used for the estimation of energy and water consumption at different operating conditions such as variable wet bulb temperatures or variable air flow rates. Zalewski and Gryglaszewski[2] discussed the heat and mass transfer processes in evaporative fluid coolers. They present a new mathematical model of evaporative cooling with counter-current air flow.

Joudi et al. [4] conducted a study on the application of the indirect evaporative coolers for the fulfilment of the variable cooling load of a typical Iraqi dwelling. They selected a two-story house located in Baghdad as the object of the study. Costelloe and Finn [5] quantify the evaporative cooling availability for northern and southern European cities and suggest a method of analysing such data for any location in the world with the help of suitable meterological records. The paper draws on the recent experimental research findings and basis the availability analysis on meterological weather data on a reference test year.

Guo et al. [6] discuss the parametric study of an indirect evaporative cooler. Thermal performance of an indirect evaporative cooler is analyzed numerically. Effect of different parameters on thermal performance is investigated. They found that smaller channel width, lower inlet relative humidity of the secondary air stream, lower velocity of the stream at inlet give high effectiveness.

Fig. 1 shows a schematic of an indirect evaporative aircooler. Indirect evaporative cooling system cools the outdoor air without adding moisture to the air. Heat exchanger is the essential component of the indirect evaporative cooler.An indirect evaporative cooling process has two distinct air passages, one named the primary or comfort air passage and the other the secondary or the humid air passage. Comfort air which is outdoor air flows over the dry side of heat exchanger. Humid air which flows over the wet side of heat exchanger is in direct contact with circulating water sprayed downward and exchanges both heat and moisture. The comfort air is not in direct contact with water and is cooled by the evaporation of water into humid air.

DOI: 01.IJPIE.02.01.58

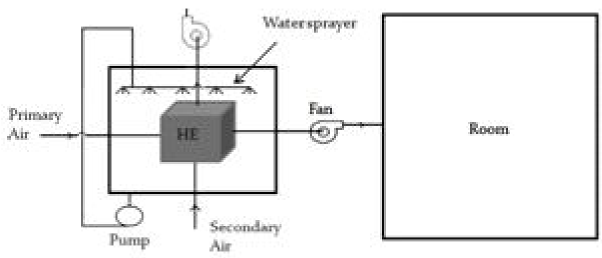

Fig 1. Schematic of indirect evaporative cooler

II. EXPERIMENTAL SETUP

Indirect evaporative cooler takes the advantage of evaporative effects but cools the air without increasing the humidity. Fig. 2 and Fig. 3 show the images of indirect evaporative cooler. It has an inbuilt cross flow heat exchanger.

Specifications of the Experimental Setup:

Heat exchanger dimensions	: $350 \times 350 \times 250$(mm^3)
Straw dimensions (L, OD, ID)	: 250, 4, 5(mm)
Number of straws	: 1958
Volume flow rate of comfort air	: 4 m^3/min
Volume flow rate of humid air	: 5 m^3/min
Velocity of comfort air	: 5 m/s
Mass flow rate of water	: 6 kg/min

The material used for the experimental setup was a Perspex sheet of 12 mm thickness. The heat exchanger is made up of plastic drinking straws (length of 250mm, inside diameter 4mm and outside diameter 4.5mm). Water from the top tank drips on the straws and a thin layer of water film forms around straws. Atmospheric air is blown across the straws from the bottom tank and causes evaporation from the falling water drops and the water film around the straws becomes cool and this cool film extracts heat from the comfort air which is passed through straws.

The comfort air becomes cool and is sent into the room. A tower fan is mounted at the front side of the cooler to suck the comfort air through the straws. A blower is mounted at the back side of the cooler for the humidified air. It sucks the atmospheric air and blows it across the straws. Small holes of 1 mm diameter were made on the bottom side of top tank and also a cotton cloth was used to ensure the uniform and continuous falling of water drops from the top tank.

For conducting the experiments, a separate closed chamber was constructed. The size of the chamber is 3.7mx2.7mx3.2m. Two walls of the chamber are made of particle board and glass, third side is the brick wall and the forth side is of plywood. For providing thermal insulation, thermocole of 100mm thickness is provided on all the six faces of the chamber.

Fig 2. Image of the cooler seen from front view

Fig 3. Image of the cooler seen from side view

III. RESULTS & DISCUSSIONS

A. Experimental Chamber Characteristics

Experiments were conducted to characterize the chamber. The experimental results are compared with the analytical values obtained by solving the one dimensional transient heat conduction equation. Fig. 4 shows the comparison of the temperature measured inside the room with a thermocouple and the temperature obtained by solving the one dimensional transient heat conduction equation.

DOI: 01.IJPIE.02.01.58

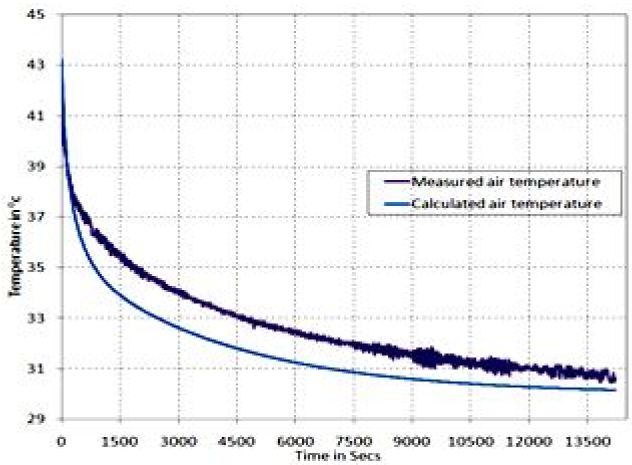

Fig 4. Comparison of measured and calculated temperatures of the comfort air

B. *Evaporative cooler performance at temperatures higher than ambient temperature*

Experiments were conducted at temperatures higher than the ambient temperature. A heat convector was used as the source of heat. Once the specified temperature is reached the heat convector and the cooler were switched on throughout the experiment. The duct between the cooler and fan is insulated using nitrile rubber to arrest the heat leak from the surroundings to the comfort air. Fig. 5 shows the typical temperature variations with time. The fluctuations in the ambient temperature are because of the thermostat placed in the heat convector.

The temperature of the inlet humid air is slightly higher than the temperature of the comfort air at inlet of the straws; this higher temperature is due to the heat added by the humid air blower. The net cooling obtained in this experiment is around 5°C. Fan adds some amount of heat to the comfort air. Because of this there is a raise of temperature of about 0.7°C in the comfort air between cooler and the fan. The humid air cools down from inlet to outlet. The water temperature is almost constant (change is less than 1°C) along the height of the cooler. Table I shows the mean temperatures of all air streams for different sets of experiments.

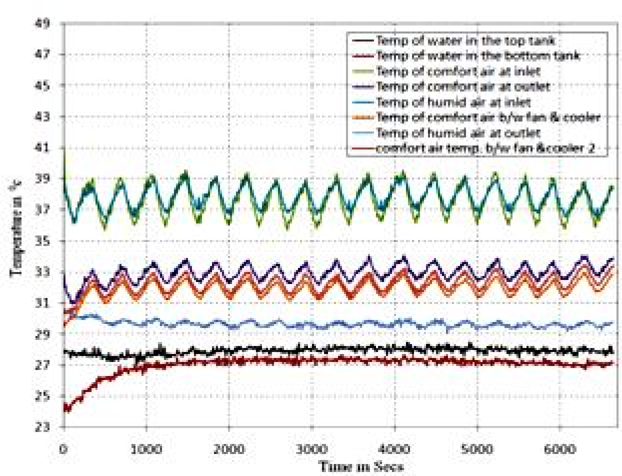

Fig 5. Variations in various temperatures with time

C. *Evaporative cooler performance at ambient temperature*

Experiments were carried out at room temperature with out the heater. Fig. 6 shows the typical temperature variations with time. The temperature of the inlet humid air is slightly higher than the temperature of the comfort air at inlet of the straws; this higher temperature is due to the heat added by the humid air blower. The net cooling obtained in this experiment is around 1.2°C.

Fan adds some amount of heat to the comfort air. Because of this there is a raise of temperature of about 0.7°C in the comfort air between cooler and the fan. The humid air cools down from inlet to outlet. The water temperature is almost constant (change is less than 1°C) along the height of the cooler. Table II shows the mean temperatures of all streams for different sets of experiments conducted at ambient temperature.

TABLE I. Mean temperatures of all air steams for different sets of experiments

	Comfort air					Humid air				Water		Net
Expt.	Inlet		Outlet		Before fan	Inlet		Outlet		Top tank	Bottom tank	cooling
Sr no.	Temp (°C)	RH (%)	Temp (°C)	RH (%)	Temp (°C)	Temp (°C)	RH (%)	Temp (°C)	RH (%)	Temp (°C)	Temp (°C)	Temp (°C)
1.	37.67	40	33.04	52.4	32.13	37.94	40.1	29.64	98.7	27.98	27.25	4.63
2.	37.38	40.8	32.75	53.3	31.78	37.61	41.7	29.36	99.3	27.73	27.05	4.63
3.	37.64	39	32.83	51.5	31.65	37.83	47.5	28.87	99.8	27.49	26.73	4.81
4.	38.65	36.3	33.37	48.7	32.16	38.69	36.9	28.95	99.6	27.85	27.06	5.28
5.	38.24	38.3	33.48	50.3	32.5	38.11	39.5	28.36	99.9	28.12	27.23	4.76
6.	36.85	39.7	32.58	51	31.67	36.87	41.4	27.87	99.5	27.24	26.48	4.27
7.	44.27	26.8	36.9	39.9	35.33	43.25	29.7	29.25	100	30.2	29.03	7.37

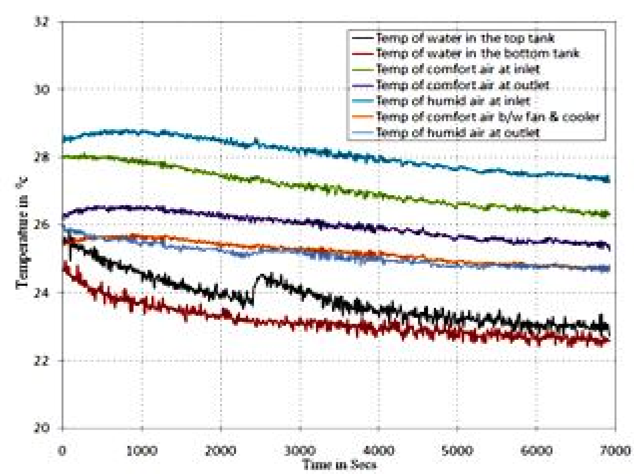

Fig 6. Variations in various temperatures with time at room temperature

DOI: 01.IJPIE.02.01.58

TABLE II. MEAN TEMPERATURES OF ALL AIR STEAMS FOR DIFFERENT SETS OF EXPERIMENTS

	Comfort air					Humid air				Water		Net
Expt.	Inlet		Outlet		Before fan	Inlet		Outlet		Top tank	Bottom tank	cooling
Sr. no.	Temp (°C)	RH (%)	Temp (°C)	RH (%)	Temp (°C)	Temp (°C)	RH (%)	Temp (°C)	RH (%)	Temp (°C)	Temp (°C)	Temp (°C)
1.	25.9	65.9	24.83	75.4	24.24	27.04	68.8	24.64	94.8	22.57	22.28	1.07
2.	26.95	65.7	25.87	72.4	25.14	27.98	66.5	25.02	97.8	23.6	23	1.08
3.	25.46	67.2	24.3	73.9	23.58	26.3	68	24.9	90.8	22.06	21.6	1.16
4.	25.81	61.4	24.32	68.8	23.56	26.7	61.9	24.87	89.4	21.95	21.4	1.49
5.	24.93	67.5	23.86	75	23.15	25.96	68.1	24.35	91.7	21.86	21.45	1.07

D. COMPARISON OF EXPERIMENTAL AND CALCULATED RESULTS

An analytical model is developed to validate the experimental results. We observed experimentally that there is not much change in the water temperature with the height of the cooler, so we assumed constant water film temperature on the surface of the straw and solved for the outlet temperature of the comfort air. The schematic of the drinking straw is shown below in Fig. 7

Fig 7. Schematic of the drinking straw

For a constant wall temperature and for laminar flow inside the tube

$$Nu = \frac{hD}{k} = 3.66$$

$$\dot{Q} = h(T_s - T_m)dA_s \qquad \text{Where} \qquad \dot{Q} = \dot{m}c_p dT_m$$

$$\frac{dT_m}{T_s - T_m} = \frac{3.66 * \pi * K}{(\rho * a * v)c_p} . d_x$$

$$T_2 = T_s - (T_s - T_1)e^{\left[\frac{-3.66 * \pi * k * x}{(\rho * a * v)c_p}\right]}$$

$$T_2 = T_s - (T_s - T_1)e^{\left[\frac{-x/d}{(0.068306 * v * d/\alpha)}\right]}$$

Fig. 8 shows the comparison of experimental and analytical values of comfort air temperature at out let of the straws at temperatures higher than the ambient temperature. The fluctuations in the temperature measurement are because of the thermostat placed in the heat convector. There is a close match between the analytical and experimental values. The slight difference is because of the assumptions taken while validating analytically.

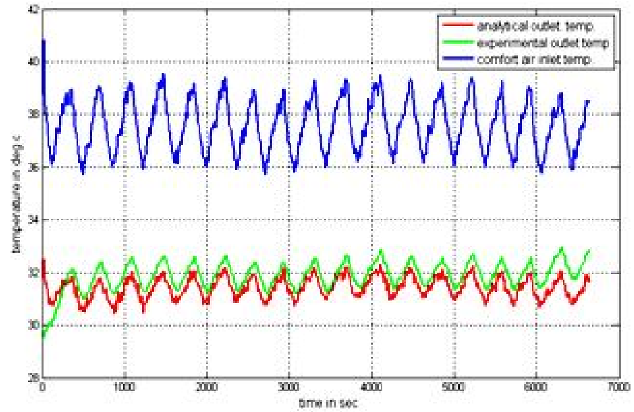

Fig 8. Comparision of experimental and analytical values of comfort air outlet temperatures.

E. Temperature variation along the length of the tube:

Fig. 9 shows the variation in outlet temperature of the comfort air along the length of the tube. The comfort air outlet temperature curve decays exponentially. Theoretically the outlet temperature of the tubes can reach the wet bulb temperature of the incoming air. For a tube diameter of 2mm and remaining parameters are same as the experimental setup values the outlet temperature of the comfort air almost reaches the wet bulb temperature of the incoming air.

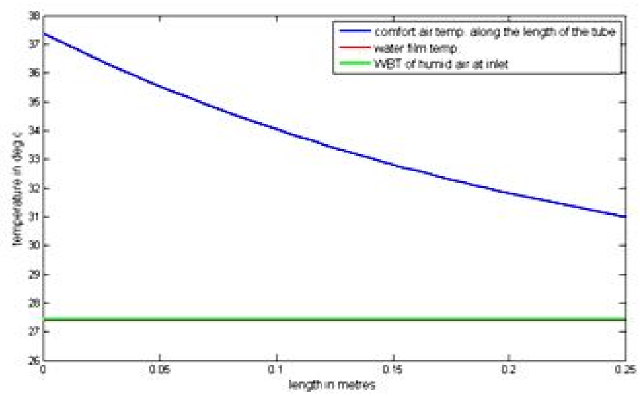

Fig 9. Variation of comfort air temperature along the length of the tube

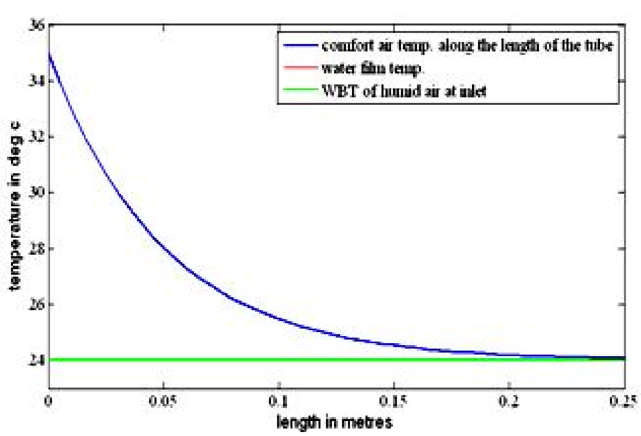

Fig 10. Variation in outlet temperature of the comfort air along the length of the tube

DOI: 01.IJPIE.02.01.58

F. Temperature variation along the length of the tube with 2mm diameter of tube:

For a straw diameter of about 2mm, with our experimental setup inlet parameters, the outlet temperature of the comfort air almost reaches the wet bulb temperature of the inlet air. So the optimum diameter of the tube is 2 mm for our experimental setup.

With 2mm as the diameter of the tube and remaining parameters are same as the experimental setup values we calculated the outlet temperature along the length of the tube and plotted. Fig. 10 shows the variation in outlet temperature of the comfort air along the length of the tube.

CONCLUSIONS

A small indirect evaporative cooler is designed and built as a cross flow heat exchanger. Experiments were conducted to evaluate the performance of the cooler under different ambient conditions (for different inlet temperatures ranging from 25^0c to 45^0c).

The analytical results shows that less relative humidity, low velocity of comfort air and an increase in the inlet temperature of comfort air gives higher cooling effect. For a given inlet conditions and for given length of the tubes the optimum diameter of the tube is 2 mm gives better cooling effect for our experimental setup .

REFERENCES

[1]Marchio, D. and Pascal, S., Simplified model for indirect- direct evaporative cooling tower behavior, Applied Energy, vol. 78, pp 433-451, 2004.

[2] W. Zalewski and Gryglaszewski P. A., Mathematical model of heat and mass transfer processes in evaporative fluid coolers, Chemical engineering and processing vol. 36, pp 271- 280 (1997).

[3] W. Zalewski, Mathematical model of heat and mass transfer process in evaporative condensers, Int. J. Refrig. 16(1), pp. 23-30 (1993).

[4] Joudi, Khalid A. and Mehdi, Salah M., Application of indi rect evaporative cooling to variabledomestic cooling load, Vol. 41, No. 17, pp. 1931-1951 (2000).

[5] Costelloe, B. and Finn,D., Indirect evaporative cooling poten tial in air-water systems in temperature climates, Energy and Buildings, Vol. 35, pp. 573-591 (2003).

[6] Guo, X. C. and Zhao, T. S., “A parametric study of an indirect evaporative cooler”, International Communications in Heat and Mass transfer, vol. 25, pp. 217-226, 1998.

[7] Suri, R. K., Raghom, Al. F., and Maheshwari, G. P., “Energy saving potential of an indirect evaporative cooler”, Applied Energy, vol. 69, pp 69-76, 2001.

[8] Jain, D., “Development and testing of two-stage evaporative cooler”, Building and Environment, vol. 42, pp. 2549-2554, 2007.

[9] Datta S., Sahgal P.N, Kishore V.V.N. and Dhingra S.C., Design and operating characteristics of evaporative cooling systems, Int. J. Refrig. Vol 10 (1987).

[10] Wang, S.K. and Lavan Z., “Air-conditioning and Refrige ration”, Ed. Frank Kreith, CRC Press LLC, 1999

DOI: 01.IJPIE.02.01.58